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published in

NIC Symposium 2016
K. Binder, M. Müller, M. Kremer, A. Schnurpfeil (Editors)

Forschungszentrum Jülich GmbH,
John von Neumann Institute for Computing (NIC),
Schriften des Forschungszentrums Jülich, NIC Series, Vol. 48,
ISBN 978-3-95806-109-5, pp. 291.
http://hdl.handle.net/2128/9842

Very High Resolution Simulations of African Climate with the Regional Climate Model REMO

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The regional climate model REMO is used to perform high resolution simulations of African climate. Simulated seasonal precipitation is analysed and compared to a lower resolution run and observational data. We show that the high resolution model is able to represent small scale features of the precipitation distribution and therefore demonstrates considerable improvement compared to the lower resolution version. We also assessed the performance of REMO on the JUQUEEN supercomputer (Jülich Supercomputing Centre, JSC) and found, that it is not the optimal system for conducting regional climate model simulations. Computers with architecture similar to JUROPA or JURECA (JSC) are better suited for this type of applications.

1 Introduction and Motivation

Findings of the 5^{th} IPCC Assessment report (IPCC AR5) released in the year 2013 indicate that the African continent is a hotspot of future climate change. In order to be able to develop options and strategies to adapt to climate change spatially, very detailed climate change information and subsequent climate change impact assessments are required. Therefore the current generation of climate models has to be continuously developed and improved to be able to provide reliable high-resolution climate change information.

The latest generation of global circulation models used in the fifth Coupled Climate Intercomparison Project (CMIP5[1]), which is the basis for IPCC AR5 Africa chapter[2], still only delivers rather coarse scale information on future climate change. Therefore dynamical and statistical downscaling of future climate change projections is required to deliver information on a scale to be used for regional to local climate impact assessments. Hence, the regional climate modelling community launched the CORDEX (Coordinated Regional Climate Downscaling Experiment), which delivers a multi-model multi-scenario ensemble of downscaled climate change information at a spatial resolution of 0.5° (all continents) and 0.11° (Europe only) for almost all inhabited regions of the world[3].

Nevertheless, for defining local scale adaptation strategies even CORDEX does not deliver data on a scale that is able to represent local climate features. Hence a further step to provide very high resolved regional climate change projections has to be made. However, running regional climate models on a very high spatial resolution requires a large amount of computational resources. Therefore simulations are either conducted for rather small regions or for only a very short time period.

In this paper we describe the findings of an initial sensitivity experiment with the regional climate model REMO[4] at a spatial resolution of 0.11° covering the whole African continent. To conduct this simulation, REMO has been implemented at the JUQEEN supercomputer in the Jülich Supercomputing Centre (JSC). REMO is a well-known regional climate model which has been used and analysed several times over Africa. Within the CORDEX initiative several simulations have been conducted with REMO for current and future conditions[5–7]. Already earlier the added value of using REMO at a relatively high horizontal resolution of approximately 18 km could be demonstrated over south-western Africa[8].

Due to the large amount of computational resources required we conducted only a one-year sensitivity experiment so far. Results of this experiment with respect to the simulation of main atmospheric conditions over Africa will be compared to the REMO CORDEX-Africa hindcast simulations. On top of this analysis also the performance of REMO on the JUQUEEN high performance computing system is analysed. Based on the findings of these assessments it will be decided if an extension of the simulation to longer time periods and maybe also for downscaling of the future climate is worthwhile.

2 REMO Model and Experiment Setup

2.1 Model Description

The sensitivity simulation described in this paper is conducted with the three-dimensional hydrostatic limited-area atmospheric model REMO (version 2009). The hydrostatic version of the regional climate model REMO has been described in several publications before in detail[9,4] and is credible to be used down to a horizontal resolution of approximately 10 km. In the following, we briefly mention the main characteristics of REMO.

The dynamical core of REMO as well as its discretisation in space and time are based on the Europa-Model of the German Weather service[10]. In the original version of REMO the physical parameterisations were taken from the global climate model ECHAM version 4[11]. The prognostic variables are surface pressure, horizontal wind components, temperature, water vapour, liquid water, and cloud ice. More detailed description of the model can be found in Ref. 4, 6, 12.

2.2 Experiment Setup

REMO was run at a horizontal resolution of 0.11° over the whole African continent (see Fig. 1). The domain was chosen in a way that it reflects the boundaries of the CORDEX Africa simulation domain (see Nikulin[5] for details). To span the domain 901 x 901 gridboxes are required in north-south and east-west direction, respectively. With a total of 811891 gridboxes this domain is about 17 times larger than the standard CORDEX Africa domain. To resolve the vertical component 31 vertical layers were used.

With this very large domain only a short simulation period could be calculated for this first sensitivity study. Hence, existing and already in equilibrium state soil moisture and soil temperatures were taken from the REMO CORDEX-Africa hindcast experiment[5] and

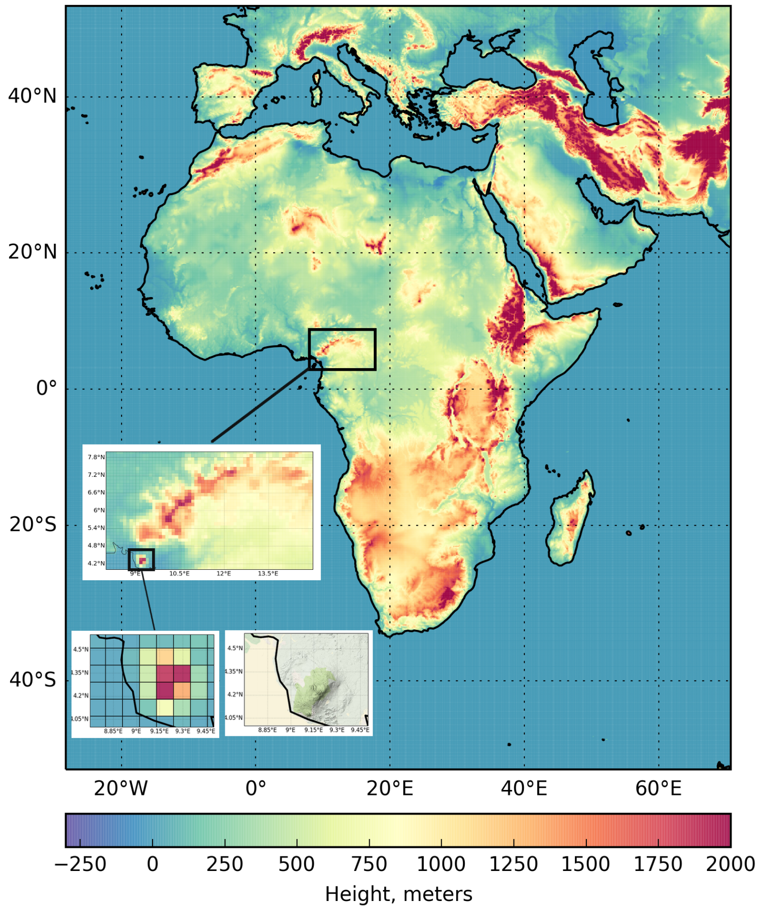

Figure 1. Orography. Zoom to mount Cameroun.

remapped onto this domain in order to reduce the spin-up time to six months. After spin-up, REMO was run for the full year 1979. Lateral boundary conditions for this sensitivity simulation were taken from ERA-Interim reanalysis.

2.3 Parallelisation and Performance

REMO is parallelised using MPI. The model domain is split up into several subdomains which are distributed among CPU cores. Each subdomain has overlapping gridboxes with neighbouring subdomains (halos), so that the information between subdomains can be transferred. This information exchange has to be performed every time step so considerable amount of interprocess communication is required. From our previous experience on another high performance computing systems, the optimal number of grid boxes for a subdomain is about 400 per core.

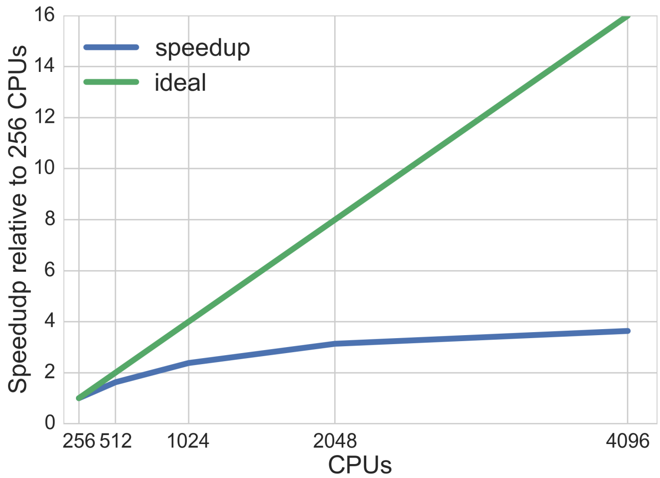

Figure 2. Scaling behaviour of REMO on JUQUEEN at JSC. This data was obtained with a domain size of 901 x 901 grid-boxes.

The amount of memory required by each CPU depends on the size of the model sub-domains and usually is about 4 GB per core. This memory is used for storing fields of the model's prognostic and diagnostic variables as well as the boundary condition fields. The IO of REMO is not parallel, so all reading and writing is done by one process. The snapshots of two dimensional fields are usually stored every model hour, while snapshots of three dimensional fields are stored every six hours. The amount of data generated by the model depends on the size of the model domain, frequency of the snapshots and number of variables. In the present experiment one model month generates about 430 GB of output data, that makes it 5 TB for one year.

2.3.1 Performance on JUQUEEN

We perform our experiment on the JUQUEEN supercomputer, that has 28,672 nodes equipped with IBM PowerPC© A2, 1.6 GHz CPU cores, 16 cores per node. The amount of memory per node is 16 GB, so there is only 1 GB per core available. As mentioned before this amount of memory is not enough for REMO, so we had to use a reduced number of CPU cores per node (2 CPUs instead of 16 for some configurations). Since CPU time is accounted on the basis of the actual node usage, huge amounts of CPU time were charged, but only a small fraction of cores was actually computing. This has to be taken in to account when one is planing to use geophysical models on JUQUEEN.

As can be seen on the Fig. 1, the model's performance does not scale very well with an increase of CPU cores used and reaches the plateau relatively fast. The limiting factor here is probably the substantial amount of inter-process communications which is consistent with our previous experience on other high performance computing systems.

Based on our findings, we conclude that the JUQUEEN is more suitable for pure dynamical applications, e.g. turbulence. However when the physics starts to play a big role, and therefore the payload of each individual processor significantly increases, JUQUEEN, with its relatively slow processors becomes inefficient. Large amount of physics related computations are characteristics for most of the ocean and atmospheric models and in REMO it is ca. 80% of the processor time. On the contrary, our experience with running REMO on JUROPA and its successor JURECA with their larger amount of available memory and faster processors is very positive and we advise to use supercomputers that use a similar architecture for geophysical applications.

3 Model Results

In order to estimate the quality of the sensitivity simulations various output fields of REMO have been validated against observations. Here we only present the analyses of the seasonal cycle of total precipitation for the REMO $0.11°$ sensitivity simulation ($REMO_{11}$) compared to the 50 km REMO CORDEX-Africa hindcast simulation ($REMO_{50}$) as well as to the CRU gridded observation set[13]. Although the various datasets included into the analysis cover different time periods (only the year 1979 for $REMO_{11}$ versus the five year period from 1979 to 1984 for $REMO_{50}$ and CRU), the analysis still allows to identify, if the major precipitation features are skillfully reproduced in the high-resolution simulation.

Generally, seasonal rainfall characteristics over most parts of Africa are strongly linked to the position of the ITCZ, leading to a pronounced annual cycle with an extended rainy and dry season, respectively, over large parts of the continent. Only in the tropical regions closer to the equator two rainy seasons are present. On top of the strong rainfall seasonality, the huge precipitation gradient between the tropics (more than 2000 mm/yr in the Congo basin region) and the desert regions in the north and south makes it difficult for climate models to simulate the precipitation amounts in the right magnitude.

On a regional scale, both the temporal and spatial precipitation patterns represented by the REMO model simulations are skillful. In general, there seems to be a rather small difference in simulated seasonal mean precipitation in the $REMO_{11}$ and $REMO_{50}$ simulations (Fig. 3) with a tendency towards wetter conditions in the spatially higher resolved $REMO_{11}$ simulation. When compared to the CRU dataset, a general dry bias of about 60 to 70 % persists for the whole year in both REMO simulations in the region around the Lake Victoria. Additionally a wet bias is present over south-eastern parts of southern Africa during the rainy season from September to March (up to about 60 to 80% during peak rain season). This wet bias has been reported before and seems to be related to an overestimation of the seasonal heat low conditions in REMO[8].

Nevertheless while interpreting the results of the sensitivity simulation, two things have to be kept in mind. First, in the high-resolution simulation the seasonal mean of only one year is compared to the average seasonal mean of five years. Hence also the year-to-year variation of precipitation, which is known to be quite substantial over large parts of Africa (e.g. Ref 14,15), could lead to enhanced biases. Second, also the CRU gridded observation set is not perfect as it is compiled on the basis of a limited number of station records and therefore includes artefacts due to interpolation over large areas[13].

The differences between the two REMO simulations might also occur due to a set of parametrisations which might not fully represent the spatial scale of the simulation. Especially the parametrisation of cloud processes is linked to the horizontal resolution and

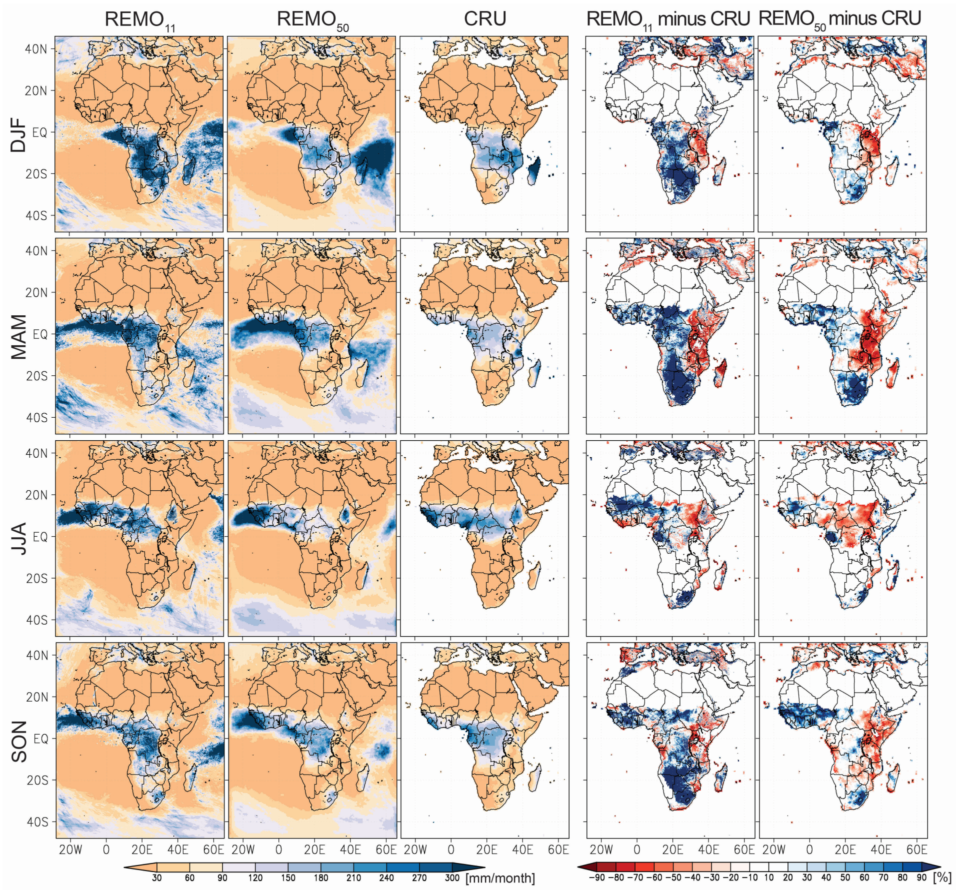

Figure 3. Precipitation in DJF and JJA for REMO_{11}, REMO_{50} and CRU data.

potentially need to be adapted to the scale, particularly when simulating over tropical regions. However, as a starting point, we used the identical parametrisation for this sensitivity simulation as was used in the REMO_{50} simulation.

More interesting than the larger regional scale features is the simulation of more complex small scale features. A good example in Africa is the Mount Cameroon region, at the coast of Cameroon. This is the region that receives more than 11000 mm of precipitation a year, which is the maximum annual rainfall amount over the whole of Africa. Fig. 4 shows a zoom of simulated annual precipitation sum over that region. Here the improved representation of complex topographic features in the higher resolved REMO_{11} simulations leads to a more realistic representation of annual precipitation sums compared to lower resolved simulations and also compared to the gridded observation datasets.

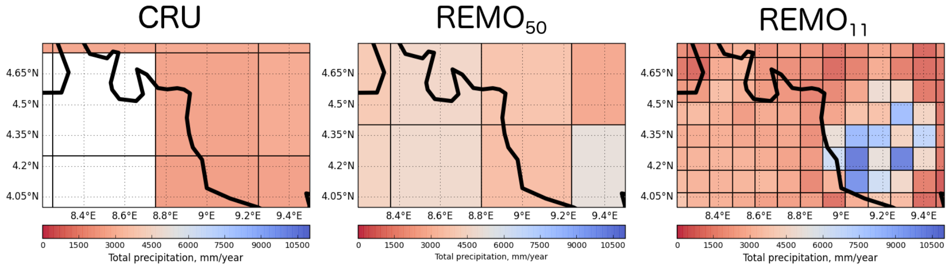

Figure 4. Simulation of small scale features in $REMO_{11}$ compared to $REMO_{50}$ and CRU data for the Mount Cameroon region. For orography of the region see Fig. 1.

4 Concluding Remarks

We have described the results obtained by a high resolution simulation with the regional climate model REMO over the African continent and our experience in using the JUQUEEN supercomputer at JSC for this computational very demanding run.

We identified that the model realistically reproduces the major spatial and temporal patterns of seasonal mean precipitation. Remaining biases might be linked to imperfect model parametrisations for this high spatial resolution; however more sensitivity tests have to be done to be able to better judge on this. Additionally, we showed that a better representation of very complex terrain in the high-resolution simulation leads to a better representation of the precipitation amounts along these features, when compared to lower resolved simulations. Hence this underlines the need for spatially detailed climate change information in order to be able to design and shape future adaptation and mitigation measures on the local scale.

Regarding the REMO performance on the JUQUEEN, we found that the performance is limited by the relatively small amount of memory available for one CPU core. Other limiting factors are the relatively low speed of the individual processors and inter process communications. The later is not unique for the JUQUEEN system, but is a common problem when running geophysical models on high performance computer systems.

Acknowledgements

The computations were performed with a grant of computer time provided by the Forschungszentrum Jülich. NK is supported by the funding from the Federal Ministry of Education and Research, Germany, for GLACINDIA project (contract 033L164).

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